GRASSROOTS JOURNALS

Grassroots Journal of Natural Resources, Vol.8 No.1 (April 2025)
ISSN: 2581-6853 | CODEN: GJNRA9 | Published by The Grassroots Institute
Website: https://grassrootsjournals.org/gjnr | Main Indexing: Scopus and WoS

ISSN 2581-6853 | 8(1) April 2025

M – 00493 | Research Article

Remote Sensing and GIS in the Research of Young River Landscape

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How to cite this paper: Pasichnyk, M., Yushchenko, Y., Palanychko, O., Melnyk, A. and Darchuk, K. (2025). Remote Sensing and GIS in the Research of Young River Landscape. *Grassroots Journal of Natural Resources*, 8(1): 163-189. Doi: https://doi.org/10.33002/nr2581.6853.080106

Received: 11 February 2025
Reviewed: 06 March 2025
Provisionally Accepted: 15 March 2025
Revised: 31 March 2025
Finally Accepted: 01 April 2025
Published: 11 April 2025
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Abstract

This article explores the integration of remote sensing (RS) and geographic information systems (GIS) for analysing the dynamics of young river landscapes, focusing on hydromorphological processes such as erosion, sediment deposition, flooding, and floodplain development. Specifically, satellite data from Sentinel-1, Sentinel-2, and Landsat 8–9 were examined using EO Browser, QGIS, and ArcGIS to assess the morphological changes of the Prut and Cheremosh Rivers. The study demonstrates that Sentinel-1 radar imagery effectively captures channel shifts during flood events regardless of cloud cover, whereas Sentinel-2's higher spectral resolution offers refined water-body delineation and floodplain analysis. Landsat 8–9 data provide a robust historical archive, useful for long-term monitoring of hydromorphological evolution. By combining multiple satellite missions, researchers can distinguish between active channel-forming zones during high-flow conditions and exposed alluvial deposits in low-flow periods. Key findings include identifying flood extent, measuring channel-width variations, and detecting specific areas prone to erosion and sediment buildup. Spectral indices were used to track moisture gradients and delineate floodplain boundaries, revealing high-value habitats and priority zones for conservation. These findings underscore the critical role of RS and GIS methods in enhancing flood risk assessment and guiding sustainable management practices within river basins. This research confirms that integrating satellite data and geoinformation technologies significantly strengthens water resource management and environmental monitoring strategies. Policymakers can leverage these insights to optimize land-use planning, prioritize conservation efforts, and develop science-based, sustainable frameworks for managing young river landscapes.

Keywords

GIS; Fluvial geosystems; Young river landscape; Water management; Flood risk assessment

Introduction

In the modern context of Integrated Water Resources Management (IWRM), it is crucial to consider natural-anthropogenic systems, or noosystems, which emerge from the interaction between society and nature. One of the key components of these systems is amphibious landscapes and areas along rivers and watercourses. These territories perform essential ecological functions, such as biodiversity support, regulation of hydrological processes, and water purification. They are vital for numerous flora and fauna species and play a significant role in maintaining ecological balance. Young river landscapes are dynamic and highly sensitive environments. They are shaped by hydrological and hydromorphological processes such as erosion, sediment transport, and deposition. These landscapes can rapidly transform under both natural influences and anthropogenic activities, including coastal zone development and the construction of hydraulic engineering structures. Studying young river landscapes provides insights into the processes that drive their development and enables the design of measures for their conservation and sustainable use, both as territories and as accessible water resources. Research on amphibious landscapes is essential for understanding their state and dynamics. This knowledge facilitates the development of effective management and conservation strategies, which are key to sustainable development. The integration of modern research methods, such as GIS technologies, allows for the acquisition of detailed data on the structure and functions of landscapes located along rivers.

International regulatory frameworks emphasize the importance of integrated water and land resource management. Notably, Chapter 10 of Agenda 21 (Agenda 21, 1992) recommends applying ecological landscape planning (LANDEP) to integrate environmental components such as air, water, land, and other natural resources. This highlights the necessity of preserving and managing amphibious landscapes. The Methodological Guidelines "Landscape Planning in Ukraine" (Rudenko *et al.*, 2014) also emphasize the importance of landscape planning as a tool for implementing sustainable development principles. Landscape planning includes the ecological and economic assessment of various territorial functions and the alignment of priorities with all stakeholder groups.

According to the EU Water Framework Directive (Directive 2000/60/EC, 2000)[1], the River Basin Management Plan (RBMP) is the primary tool of Integrated Water Resources Management (IWRM) aimed at protecting surface and groundwater, wetlands, and their ecosystems. The approval of RBMPs in Ukraine by the end of 2024 represents a significant step in the development of national water policy and integration with European and global water resource management standards. These plans are designed to achieve environmental objectives for each river basin district, ensuring a systematic and scientifically grounded approach to water resource utilization and conservation. Instead of a fragmented approach to managing individual rivers or administrative territories, a comprehensive basin-wide approach is implemented, which involves coordination between different government agencies, businesses, scientific institutions, and the public.

[1] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000. Establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities.*

The adoption of RBMPs is a European integration commitment of Ukraine under the Association Agreement with the EU and one of the key indicators in the "Water Quality" sector during the negotiation process for Ukraine's accession to the EU. This demonstrates Ukraine's readiness to adhere to common standards, paving the way for attracting international funding and grants to improve water infrastructure, implement modern wastewater treatment technologies, and restore natural ecosystems. In a global context, this step enhances Ukraine's reputation as a country committed to best practices in water management, fostering investment attraction and strengthening cooperation with international organizations such as the International Commission for the Protection of the Danube River, the Global Water Partnership, UN-Water, and others.

Several factors have influenced the adoption of RBMPs in Ukraine, including the urgent need to address major water and environmental challenges, such as:

- Pollution of surface waters with organic, nutrient, and hazardous substances;
- Hydromorphological alterations;
- Pollution and depletion of groundwater;
- Climate change impacts;
- Reducing the environmental footprint of infrastructure projects on water bodies;
- Littering of water bodies with household waste;
- Biological pollution (spread of invasive species);
- Impact of military actions on water resources.

Despite the ongoing war, Ukraine continues to actively implement the requirements of EU directives, particularly Directive 2000/60/EC[2], which establishes the framework for Community action in the field of water policy. The RBMPs were prepared within the deadlines set in Annex XXX to the EU-Ukraine Association Agreement and incorporate the best available expert knowledge, following the EU Common Implementation Strategy guidelines. Ukraine has drawn on the experience of Slovakia, Romania, Poland, Hungary, France, and Estonia. To develop RBMP measures, communication activities were conducted with local authorities and municipalities to ensure alignment with regional needs and challenges (WWF, 2010). The Carpathian Convention (Ministero dell'Ambiente e della Tutela del Territorio e del Mare, 2007) also envisions sustainable and integrated water resource and river basin management, promoting policies that combine sustainable water use and land-use planning. This includes the conservation of natural watercourses, lakes, springs, and groundwater resources, as well as the protection of wetlands. The integration of water and land resource management is essential for achieving sustainable development. Wetland landscapes, territories along rivers and watercourses play a crucial role in maintaining ecological balance. At the same time, these landscapes, characterized by dynamic changes and active hydromorphological processes, can be defined as young river landscapes. Their study and management are critically important for ensuring sustainable development and natural resource conservation.

This study aims to highlight effective methods for collecting, processing, and analyzing geospatial data using geographic information systems (GIS) and satellite imagery platforms for the study of young river landscapes. The main objectives of this study are:

[2] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000. Establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities.*

- Analysis of scientific literature and research on the use of GIS technologies and remote sensing (RS) methods for studying the dynamics of young river landscapes;
- Assessment of the suitability of satellite imagery from Sentinel-1, Sentinel-2, Landsat 8–9 for the identification, monitoring, and analysis of young river landscapes, considering their spatial, spectral, and temporal resolution;
- Application of modern geospatial data analysis methods (QGIS, ArcGIS, and EO Browser) to identify structural changes in young river landscapes, using the Prut and Cheremosh Rivers as case studies.

Review of Literature

To achieve the stated objectives, we present methods for identifying young river landscapes (YRL). Such research has been conducted for several decades at Yuriy Fedkovych Chernivtsi National University under the supervision of Professor Yushchenko (Yushchenko, 2005; Yushchenko *et al.*, 2022). A methodology and taxonomic system have been developed to identify and distinguish homogeneous areas of the riverbed and floodplain (HARF) and young river landscapes (YRL), incorporating geospatial analysis of river valley structures. Special attention is given to well-developed elements of flow-channel-floodplain systems (FCFS), particularly the "trunk valleys". Geomorphological and hydromorphological processes are key to explaining the genesis, identification, and geospatial analysis of young river landscapes (Yushchenko, 2019; Yushchenko, Honchar and Hryhoriichuk, 2017, Yushchenko *et al*. 2022). The methodology for identifying young river landscapes includes:

- Homogeneous areas of the valley (HAV);
- Homogeneous areas of the valley bottom (HAVB);
- Homogeneous areas of the riverbed and floodplain (HARF).

The defined features and criteria for delineating these territorial units have been tested on examples of rivers in Precarpathian Ukraine (Pasichnyk, 2012; Yushchenko, 2005). The development of these criteria takes into account published scientific works in the fields of geomorphology (Kravchuk, 1999; Polivtsev, 2011; Tsys, 1968) and paleogeography (Gebica, 2013; Huhmann *et al*., 2004). The recording of the natural territorial structure of young river landscapes is conducted using GIS technologies (QGIS and ArcGIS software) along with remote sensing (RS) data (EO Browser). Additionally, a hydromorphological database is compiled for the river basin (Yushchenko, 2022). A significant indicator in this study is the long-term channel formation zone (LTChFZ), derived from historical maps dating from the early 19th to the mid-20th century. This reflects natural river channel dynamics. The assessment of anthropogenic impacts on natural YRL is carried out using official and archival data, stream gauge observations, cartographic information, remote sensing (RS) data, and expeditionary research, including GPS surveys. The GPS survey methodology is used to determine changes in the elevation position of river channels.

Among the scientific publications evaluating the condition of rivers, riparian areas, and their catchments, there is a considerable body of research in hydromorphological, hydroecological, geoecological, and ecological-geomorphological studies. This study presents (Yushchenko *et al.*, 2022) research findings that cover young river landscapes,

highlight the research methodology using GIS technologies and RS data, and include case studies both in Ukraine and internationally. It is important to highlight the works of Professor I. Kovalchuk (Tsaryk *et al*, 2020), which are dedicated to the study of river basin systems in Western Ukraine. Their research covers river basin systems of the Ukrainian Carpathians, Zakarpattia, Precarpathian region, Podillia, Volyn Upland, and Polissia. These works integrate hydroecological, ecological-geomorphological, and landscape-ecological approaches to studying the condition of river systems and their long-term changes under the influence of various factors. An important feature of these studies is the extensive use of multi-temporal large-scale topographic maps (from 1772 to the present), thematic studies utilizing remote sensing data and geographic information systems (ArcGIS, QGIS, and others), as well as multi-temporal satellite images obtained using the SAS Planet navigation program.

Among international authors studying young river landscapes, a notable researcher is Maurizio Lazzari from the University of Basilicata and Salento in Italy (Lazzari, 2020). His expertise lies in the application of geographic information systems (GIS) for analyzing fluvial geomorphology and landscape changes. His research includes the analysis of river process dynamics, assessment of alluvial balance, and evaluation of anthropogenic impacts on river systems. Analyzing the publications of Maurizio Lazzari and his co-authors (Lazzari, 2020; Guerra and Lazzari, 2020) demonstrates the importance and effectiveness of using GIS technologies in fluvial geomorphology. The application of digital elevation models (DEMs), geomorphological mapping, and quantitative analysis methods enables the acquisition of accurate data on the condition and dynamics of river systems. This enhances monitoring, management, and conservation of river landscapes.

For more information on remote sensing of hydrological and hydro-meteorological components, it is recommended to explore the Space4Water platform. This initiative is supported by the United Nations Office for Outer Space Affairs (UNOOSA) and was established by the United Nations to promote international cooperation in the peaceful use of outer space. The primary goal of Space4Water is to utilize space technologies to address global challenges related to water resources. It is also worth paying attention to the article on Space4Water by Kitambo (2022). This publication focuses on the Sentinel-1, Sentinel-2, and Landsat 8-9 satellite missions, which provide free global data as described in table 1 and briefly discussed here, as they are essential for this study. Although the data from these satellites is openly accessible and regulated under open licenses, registration and authorization are required to access them. The following specifications of satellite imagery data should be clarified:

- Sentinel-1: Utilizes radar technology, enabling observations regardless of weather conditions and illumination, which is crucial for monitoring water bodies.
- Sentinel-2: Provides high-resolution optical images in the visible, infrared, and shortwave infrared spectra, allowing detailed analysis of surface waters, vegetation, and soils.
- Landsat 8-9: Offers multispectral imagery with high spatial resolution, useful for long-term monitoring of changes in water resources and ecosystems.

These satellite data are widely used for:

Doi: https://doi.org/10.33002/nr2581.6853.080106 Open Access

- Water body identification (detection and mapping of water surfaces);
- Meteorological data analysis (assessing weather impacts on water resources, monitoring snow and ice);
- Environmental monitoring (tracking changes in water resources related to natural and anthropogenic factors).

Methodology

The spatial resolution of the mentioned satellites varies from 5 to 100 meters, while the revisit period ranges from 5 to 16 days. The smaller the spatial resolution value, the more details can be observed in objects. Depending on the sensor type, the spectral resolution also varies. Many sensors are multispectral, covering 3 to 10 bands, whereas some are hyperspectral, containing hundreds to even thousands of bands. The spectral resolution improves when the wavelength range for a given band is narrower. For this study, we used satellite images from the EO Browser system. A key advantage of this web interface for viewing Earth satellite images is that its images, in GeoTIFF format, can be downloaded in the most common projections and integrated into GIS software environments such as QGIS and ArcGIS. The resolution indicators of different satellite missions used in this study are presented in table 1 below (Copernicus Open Access Hub, 2023; United States Geological Survey, 2022).

Table 1: Some Open-Source Remote Sensing Satellite Missions Supporting Water Flow Assessment

Satellite Mission	*Launch Date*	*Operational Period*	*Sensor Type*	*Resolution (Spatial/Temporal)*	*Data Portal*
Santinel-1	April 3, 2014	7 years with consumables for 12 years (still operational)	C-SAR (C-band Synthetic Aperture Radar)	5-20 m (8 days)	European Space Agency (Copernicus Open Access Hub)
Santinel -2	June 23, 2015	7 years with consumables for 12 years (still operational)	MSI (Multispectral Instrument)	10-60 m (5/10 days)	European Space Agency (Copernicus Open Access Hub)
Landsat 8	February 11, 2013	Still operational and expected to function for several more years	OLI (Operational Land Imager), TIRS (Thermal Infrared Sensor)	15-100 m (16 days)	United States Geological Survey (USGS Earth Explorer)
Landsat 9	September 27, 2021	Still operational	OLI-2 (Operational Land Imager 2), TIRS-2 (Thermal Infrared Sensor 2)	15-100 m (16 days)	United States Geological Survey (USGS Earth Explorer)

Sentinel-1 is an Earth observation system based on synthetic aperture radar (SAR), consisting of two identical satellites: Sentinel-1A and Sentinel-1B. It provides imagery in four different acquisition modes (Figure 1): Stripmap (SM), Interferometric Wide Swath (IW), Extra Wide Swath (EW), and Wave mode (WV), operating independently of weather conditions. The selection of the acquisition mode depends on the purpose of image capture, data transmission capacity, and overall available time for data acquisition during each orbital pass. It is equipped with an SAR system operating at a frequency of 5.405 GHz and a wavelength of 56 mm (Ahmad and Kim, 2019). In their study, Ahmad

and Kim (2019) utilized Sentinel-1 satellite imagery in Interferometric Wide Swath (IW) Ground Range Detected (GRD) mode, which is the primary acquisition mode for land and inland water bodies.

It is important to note that the spatial resolution of Sentinel-1 SAR imagery in IW-GRD mode is as follows:

- 10 meters – for images in VV (vertical transmit, vertical receive) and VH (vertical transmit, horizontal receive) polarization.
- 20 meters – for filtered and processed images after noise removal and application of processing algorithms.

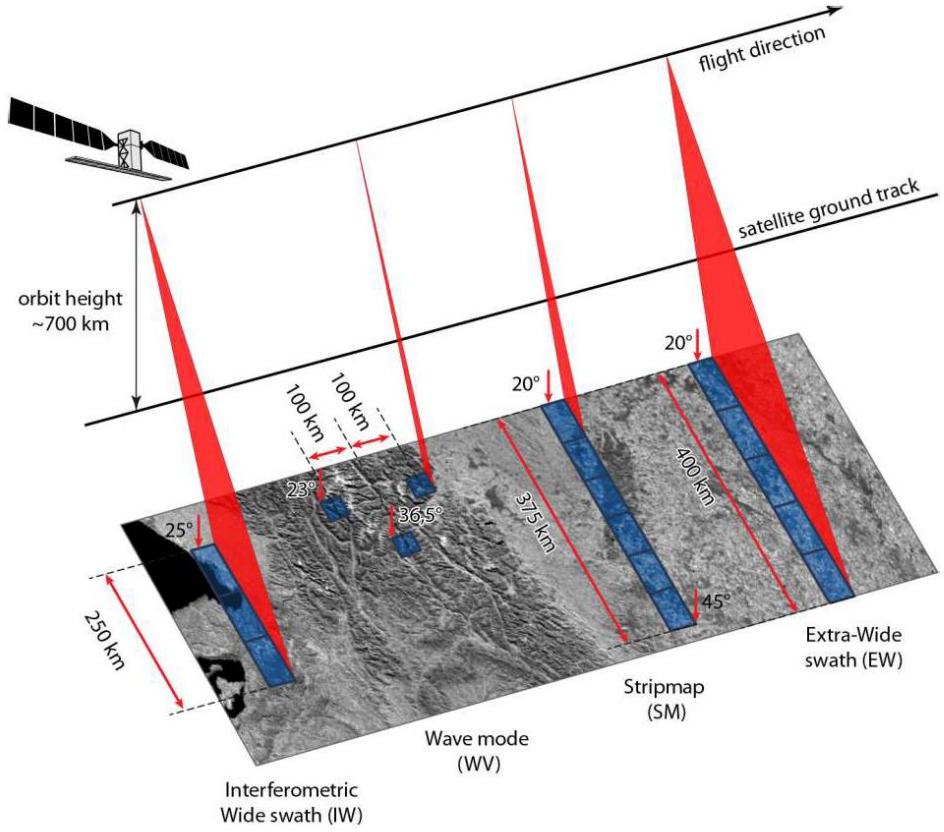

Figure 1: Different acquisition modes of Sentinel-1 satellites (European Space Agency, 2016)

The initial resolution of Sentinel-1 data is 10 meters, but after applying filtering, calibration, and detail smoothing, the final resolution for water surface analysis can be around 20 meters. This implies that the method may have certain accuracy limitations for very small rivers or narrow streams, whereas it is well-suited for medium and large rivers (Ahmad and Kim, 2019). The methodology is promising for assessing river discharge in remote areas where traditional hydrometric observations are unavailable. The use of Sentinel-1 satellite data enables regular monitoring regardless of weather conditions, which is a significant advantage in modern hydrological research.

The detection of river channels in Landsat 8–9 satellite images is based on the analysis of spectral 'signatures' of water and adjacent land surfaces in different wavelength bands. The key aspects of this process are as follows:

1. Visible and Infrared Spectral Bands (OLI):
    - Water has characteristic spectral signatures in the visible (blue, green, red) and near-infrared (NIR) bands.
    - Water absorbs most infrared radiation, making it appear dark in NIR images.
    - Vegetation and soil have different spectral signatures, allowing them to be distinguished from water.
2. Thermal Infrared Bands (TIRS):
    - These help detect water temperature, which can be useful for analyzing thermal effects and identifying water bodies.
    - Classification algorithms (e.g., maximum likelihood methods, decision tree classification) can be used to separate pixels into classes: water, vegetation, and soil.
    - The Normalized Difference Water Index (NDWI) is calculated to highlight water bodies. NDWI uses the green and NIR bands:

NDWI = (Green−NIR) / (Green+NIR)

Positive values indicate the presence of water.

Results

Analysing Sentinel-1 (SAR) images in VH polarization with radiometric terrain correction (gamma-0, dB) allows for the effective identification of key elements of young river landscapes of the Prut and Cheremosh Rivers, which undergo dynamic changes. This approach is based on the ability of water surfaces to absorb radar signals, appearing as dark areas in the images, enabling the assessment of river morphological changes during different hydrological phases. According to the study by Markert *et al*. (2020a), the use of radiometrically corrected Sentinel-1 data in VH polarization enhances the accuracy of mapping surface water bodies, particularly in complex terrain conditions. This confirms the effectiveness of this method for monitoring rivers with turbulent flow (Markert *et al.*, 2020b).

Using Space Imagery from the Sentinel-1 Satellite Mission

By analyzing Sentinel-1 (SAR) imagery (Figures 2-3), it is possible to identify key elements of the young river landscape of the Prut and Cheremosh Rivers, which are subject to dynamic changes. Based on microwave reflection in the Interferometric Wide Swath (IW) Ground Range Detected (GRD) mode, processed in VH polarization with radiometric terrain correction (gamma-0, dB), SAR images allow for the assessment of morphological changes in the river environment over the period between June 27, 2020 (Figure 2) and April 12, 2024 (Figure 3). These dates were chosen to reflect two distinct phases of the hydrological regime:

1. From June 24-27 to June 27, 2020, a flood event occurred in the Prut and Cheremosh River basins.
2. From April 12 to April 28, 2024, low-water conditions were observed in these rivers.

Doi: https://doi.org/10.33002/nr2581.6853.080106 Open Access

Thus, the selected satellite images fully represent the amplitude of water level variations in the river channels and provide insight into the potential for channel identification using satellite mission data.

By analyzing figures 2 and 3, we can conclude that river channels and their widths are well-represented in the images, as water absorbs the radar signal and appears dark. During the flood period (Figure 2), the channel is widened, indicating water overflow into the floodplain, whereas in the second image, a narrowing of the channel is noticeable, signifying low water levels.

Figure 2: Sentinel-1 SAR IW-GRD image in VH polarization with radiometric terrain correction (gamma-0, dB) of the junction of the Prut and Cheremosh Rivers (Cheremosh on the left) during the flood event, June 24, 2020

Floodplain areas can also be identified, as lighter areas around the river may indicate wet soils or temporarily flooded zones, which can remain as ephemeral water bodies after a flood. This is particularly important for the study of young floodplain terraces, which change with each flood event. The analysis of the satellite images indicates that shoreline shifts and channel displacement occurred between the two images. Such analysis helps identify areas of intense erosion on the studied rivers. In figure 3, during the low-water period, lighter areas along the river channels can also be observed, indicating accumulated alluvial sediments left behind after the water receded. This information is valuable for studying sediment deposition processes and changes in the riverbed structure.

When studying young river landscapes, it is also important to consider the use of multispectral Sentinel-2 satellite imagery, as it meets the required spatial and temporal resolution for water bodies. For water body identification, all Sentinel-2 spectral bands are used except for the atmospheric bands B1, B9, and B10. The images are processed by computing the near-infrared (NIR) and shortwave infrared (SWIR) bands to generate False Color Imagery (FCI), where water pixels stand out against the background. This

method is well described in the study by Cavallo *et al*. (2022). The analysis of Sentinel-2 mission data, particularly the spectral characteristics of the near-infrared (NIR) and shortwave infrared (SWIR) bands, enables effective research on young river landscapes. According to table 2 (Cavallo *et al*., 2022), Sentinel-2 includes the NIR bands (B8 with a range of 785-899 nm and B8a with a range of 855-875 nm), which have a spatial resolution of 10 m and 20 m, respectively. SWIR is covered by bands B11 (1565-1655 nm) and B12 (2100-2280 nm), each with a spatial resolution of 20 m.

Figure 3: Sentinel-1 SAR IW-GRD image in VH polarization with radiometric terrain correction (gamma-0, dB) of the junction of the Prut and Cheremosh Rivers during the low-water period, April 12, 2024

These bands are key for water body identification because B8 strongly reflects vegetation but is significantly absorbed by water, allowing effective separation of water surfaces from surrounding areas. B11 and B12 are sensitive to soil moisture and water levels, making it possible to identify areas with different degrees of water saturation, including flooded floodplains, moist alluvial deposits, and temporary channel structures. The B8a band enables detailed analysis of transitional moisture zones between the river channel and adjacent areas. Sentinel-2 enables spatially detailed analysis of young river landscapes due to the combination of spectral bands, which helps identify water bodies, seasonal water level changes, flooded and dry areas, channel dynamics, and the impact of moisture on shoreline structure. The spatial resolution of 10-20 meters is sufficient for analyzing such landscape components, as it allows tracking changes in channel dimensions and alluvial deposits on medium and large rivers, which typically vary within tens of meters.

Analyzing the Sentinel-2 images of the junction of the Prut and Cheremosh Rivers, captured during the flood period (June 24, 2020) and low-water period (April 12, 2024), allows us to assess their effectiveness in studying young river landscapes. Both images are examples of False Color Imagery (FCI), where near-infrared (NIR) and shortwave

infrared (SWIR) spectral bands are used to analyze water regime, soil moisture, and vegetation cover.

Table 2: Characteristics of Sentinel-2 MSI

Wavelength Range [nm]	*Spatial Resolution [m]*			*Spectral Region*
	10	20	60	
423-463			B1	Coastal aerosol
458-523	B2			Blue
543-578	B3			Green
650-680	B4			Red
698-713		B5		Red Edge
733-748		B6		Red Edge
773-793		B7		Red Edge
785-899	B8			NIR
855-875		B8a		NIR narrow
925- 965			B9	Water-Vapour
1350-1410			B10	SWIR-Cirrus
1565-1655		B11		SWIR
2100-2280		B12		SWIR

Using space imagery from the Sentinel-2 satellite mission

The 2020 image represents a flood period, where a significant portion of the floodplain is inundated. This is visible as a wide blue-black area, indicating the presence of a large volume of water, which strongly absorbs near-infrared and shortwave infrared radiation. Additionally, purple and pink shades along the shoreline and floodplain indicate water-saturated areas containing moist alluvium or shallow water zones. This corresponds to the findings of Cavallo *et al*. (2022), which emphasize that the SWIR bands (B11, B12) are highly sensitive to moisture variations, allowing for the identification of seasonally flooded areas. The 2024 image shows a significantly narrower river channel, while floodplain areas appear bright green, indicating active vegetation growth. During the low-water period, the structure of alluvial deposits becomes much more visible, particularly river bars, temporarily dry channel sections, and zones where the water has receded, leaving behind silty deposits. This confirms the potential of Sentinel-2 imagery for studying the spatial dynamics of young river landscapes, especially during low-water periods, when more details of channel morphology and texture become apparent.

Regarding moisture identification, the higher water level in the 2020 image is confirmed by an expanded area of dark blue shades. In contrast, in 2024, the SWIR reflectance of drier soils and exposed river deposits increases, causing them to appear in lighter brown and pink tones. This corresponds to the findings of Cavallo *et al*. (2022), which indicate that SWIR is a key indicator of moisture levels, allowing not only the detection of water presence but also the assessment of soil moisture content. The colors in the images help distinguish different types of underlying surfaces. Dark blue shades indicate the presence of deep water, whereas lighter purple tones correspond to shallow water or partially flooded areas. Green areas represent vegetation, with brighter shades corresponding to healthy plant cover with high biomass. Light pink and brown zones, clearly visible in

the 2024 low-water image, indicate dry alluvial deposits exposed due to seasonal water level decline.

Figure 4: Sentinel-2 (SWIR, NIR) image of the junction of the Prut and Cheremosh Rivers during the flood period (June 27, 2020)

It is worth noting that the use of Sentinel-2 for identifying young river landscapes is highly appropriate, as this mission provides an optimal combination of spatial resolution (10–20 m) and spectral coverage. Cavallo *et al*. (2022) demonstrate that Sentinel-2 accurately identifies hydrological regime changes and river system dynamics, particularly in intermittent and seasonally changing rivers. In our case, this methodology effectively analyzes water flow changes, identifies alluvial formations, and tracks flood impacts on river morphology.

Additionally, research published on the official Sentinel-2 mission website (https://sentinels.copernicus.eu) confirms the effectiveness of SWIR and NIR bands in monitoring channel changes, seasonal water dynamics, and floodplain moisture assessment. A review of European Space Agency (ESA) materials indicates that Sentinel-2 is widely used for hydrological monitoring, particularly for assessing flood risks and changes in aquatic ecosystems.

Thus, the analysis of Sentinel-2 FCI images enables high-detail studies of young river landscapes, tracking seasonal channel changes, identifying alluvial formations, and assessing moisture dynamics. The combination of NIR and SWIR allows for detailed mapping of water bodies and their interaction with the surrounding environment, which is crucial for monitoring river systems and their development. The Landsat 8–9 satellites, equipped with Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS), provide detailed mapping of water bodies and young river landscapes. These satellites capture images with a resolution of 30 meters for most spectral bands, 15 meters for the

panchromatic band, and 100 meters for thermal infrared bands, ensuring high accuracy in identifying changes in water systems and river ecosystems.

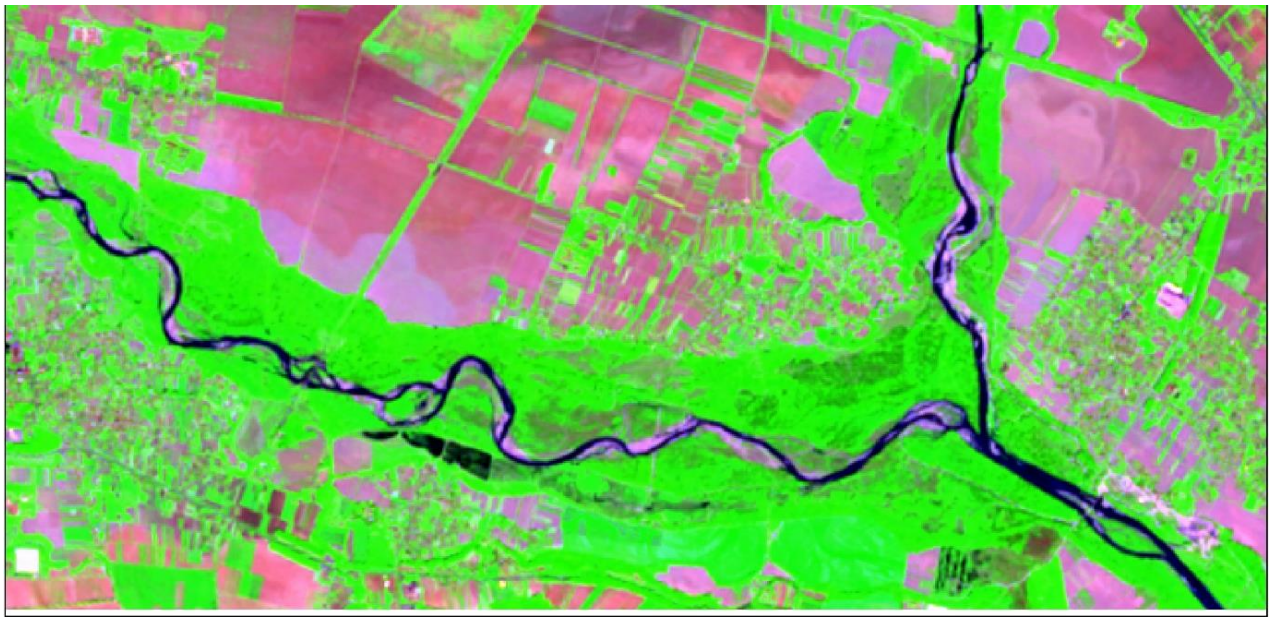

Figure 5: Sentinel-2 (SWIR, NIR) image of the junction of the Prut and Cheremosh Rivers during the low-water period (April 12, 2024) (the image was created for this paper by Pasichnyk M)

Water bodies such as rivers, lakes, reservoirs, and wetlands can be analyzed using various spectral bands sensitive to water presence, pollution, and moisture level variations. For instance, Band 1 (Coastal Aerosol, 0.43–0.45 µm) is used to assess water quality and detect suspended particles, essential for turbidity and pollution analysis. Band 2 (Blue, 0.45–0.51 µm) is useful for bathymetric mapping of shallow areas and monitoring water transparency. Band 5 (NIR, 0.85–0.88 µm) helps identify water bodies and observe shoreline changes, while Bands 6–7 (SWIR 1 and SWIR 2, 1.57–2.29 µm) assist in evaluating the moisture levels of water bodies and floodplain soils. Bands 10–11 (TIRS 1 and TIRS 2, 10.6–12.51 µm) are used for thermal mapping of water bodies, assessing thermal anomalies, and detecting pollution. A detailed description of wavelength ranges and their applications is presented in table 3.

Monitoring Young River Landscapes with Landsat 8–9

Young river landscapes, which frequently change due to natural processes and anthropogenic influences, can also be effectively tracked using Landsat 8–9.

- Band 4 (Red, 0.64–0.67 µm) is used to analyze vegetation in riparian zones.
- Band 5 (NIR, 0.85–0.88 µm) helps identify areas of active vegetation in floodplains.
- Bands 6–7 (SWIR 1 and SWIR 2, 1.57–2.29 µm) allow for the assessment of soil moisture and the identification of wetland areas.
- Band 9 (Cirrus, 1.36–1.38 µm) helps detect the presence of cirrus clouds, which can affect the accuracy of remote sensing.

- Bands 10–11 (TIRS 1 and TIRS 2, 10.6–12.51 µm) are used for flood prediction, monitoring erosion processes, and identifying flood-prone areas.

Table 3: Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS). Wavelength Bands and Their Applications. (United States Geological Survey, 2022)

Band	*Wavelength*	*Useful for Mapping*
Band 1 - Coastal aerosol	0.43-0.45	Coastal and aerosol studies
Band 2 - Blue	0.45-0.51	Bathymetric mapping, differentiating soil from vegetation, and deciduous from coniferous vegetation
Band 3 - Green	0.53-0.59	Highlights vegetation peak, useful for assessing plant vigor, and distinguishes vegetation on slopes.
Band 4 - Red	0.64-0.67	Differentiates vegetation on slopes
Band 5 - Near Infrared (NIR)	0.85-0.88	Emphasizes biomass content and shorelines
Band 6 - Short-wave Infrared (SWIR) 1	1.57-1.65	Differentiates soil and vegetation moisture; penetrates thin clouds
Band 7 - Short-wave Infrared (SWIR) 2	2.11-2.29	Enhanced soil and vegetation moisture content detection with thin cloud penetration
Band 8 - Panchromatic	0.50-0.68	15-meter resolution, sharper imaging
Band 9 - Cirrus	1.36-1.38	Improved detection of cirrus cloud contamination
Band 10-TIRS 1	10.60-11.19	100-meter resolution, thermal mapping and soil moisture assessment
Band 11 -TIRS2	11.5-12.51	100-meter resolution, enhanced thermal mapping and soil moisture assessment

The 30-meter resolution for the main spectral bands effectively enables the identification and long-term monitoring of changes in water bodies. Research confirms that this resolution is sufficient for analyzing water level fluctuations and the expansion of wetlands (journals.nau.in.ua). The 15-meter resolution panchromatic band enhances image detail, allowing for the analysis of finer river landscape features. Meanwhile, thermal bands with a 100-meter resolution are useful for detecting temperature variations in water bodies, which may indicate pollution or the presence of underground water flow.

Using Space Imagery from the Landsat 8–9 Satellite Mission

The practical significance of using Landsat 8–9 includes monitoring the condition of water bodies, detecting shoreline changes, mapping channel shifts, assessing wetland levels, and predicting natural disasters. Landsat 8–9 provide high efficiency in remote sensing of water bodies and young river landscapes, combining high spatial resolution with broad spectral coverage. This makes them an essential tool for environmental monitoring and water resource management. Satellite images from June 27, 2020, and April 28, 2024, demonstrate the effectiveness of spectral identification of water bodies at the confluence of the Cheremosh and Prut Rivers. By analyzing the color spectrum, it

Doi: https://doi.org/10.33002/nr2581.6853.080106 Open Access

is possible to determine the main landscape types and their characteristics during different hydrological periods. Both images utilize the near-infrared (NIR) spectral range, which allows for clear differentiation of water surfaces, moist soils, and vegetation cover.

The June 27, 2020, image captures a flood period, as evidenced by the expansion of river channels, flooding of adjacent floodplains, and an increased water surface area. Water bodies appear in dark blue or black shades, as water absorbs most of the infrared radiation. In flooded areas, transitional colors such as dark green and light blue indicate the presence of water and high soil moisture levels. Clouds visible in the image appear bright white, characteristic of their high albedo in the near-infrared spectrum. The April 28, 2024, image represents the low-water period, when river water levels are at their lowest, and the water balance is in a stable state. Water bodies have significantly decreased in size, river channels have narrowed, and floodplain areas have become covered with vegetation. The well-defined river contours confirm the normalization of the hydrological regime. Vegetation in both images appears bright red, indicating its active photosynthetic activity. The red hues are particularly saturated in densely vegetated areas, especially in floodplains and agricultural fields.

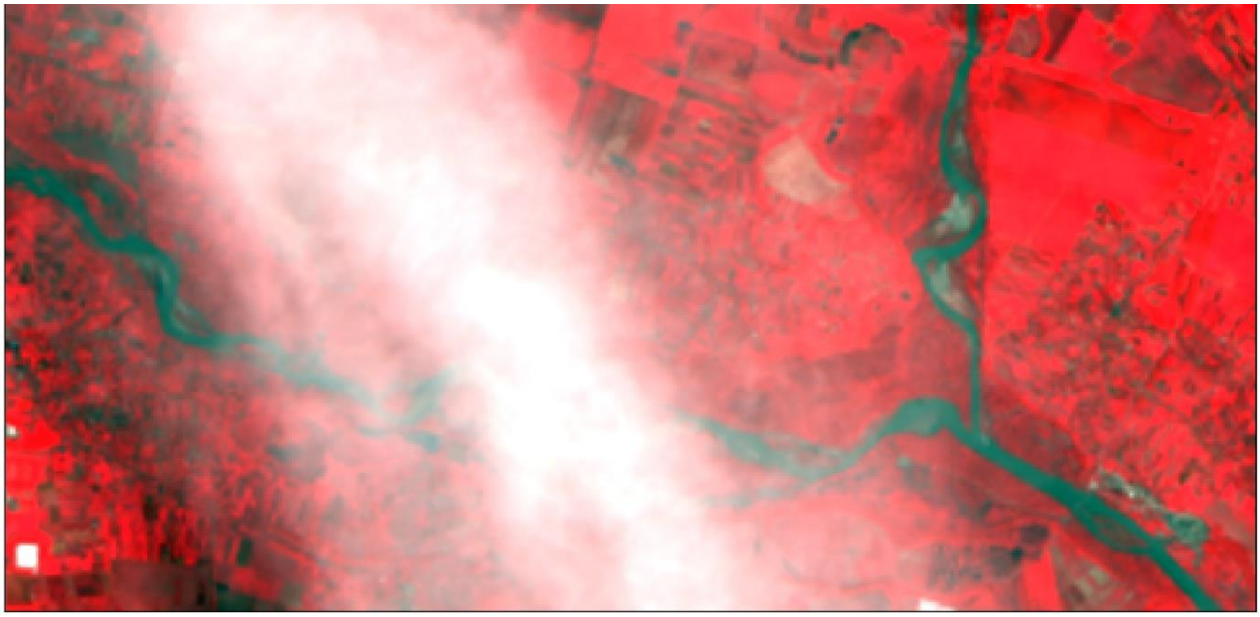

Figure 6: Landsat 8-9 (SWIR, NIR) image of the confluence of the Prut and Cheremosh Rivers during the flood period (June 27, 2020)

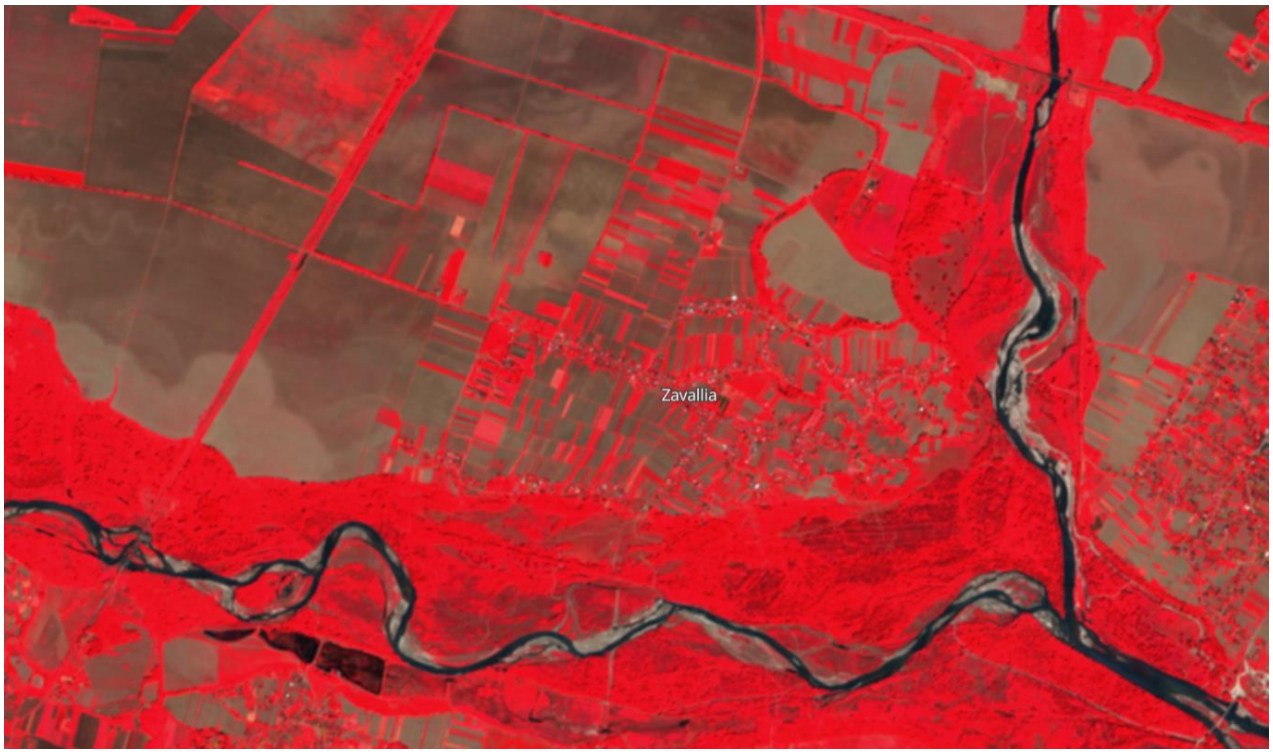

Figure 7: Landsat 8-9 (NIR) image of the junction of the Prut and Cheremosh Rivers during the low-water period (April 28, 2024)

Color Spectrum and Corresponding Landscape Types:

- Dark blue or black – Water bodies (deep river sections, lakes, flood zones).
- Light blue or dark green – Moist soils, temporarily flooded areas.
- Bright red – Active vegetation (meadows, forests, crops).
- Dark red or brown – Less moist vegetation, bare soil, or degraded areas.
- Light brown and gray – Agricultural fields with minimal vegetation cover.
- White – Clouds or other atmospheric phenomena reflecting infrared radiation.

Analyzing this data allows for an accurate assessment of the 2020 flood extent, identification of flood zones, and comparison with the low-water state of 2024. The use of the Normalized Difference Water Index (NDWI) combined with SWIR analysis helps refine the boundaries of water bodies and determine the areas that have undergone the most significant changes. Landsat 8-9 and Sentinel-2 images enable metric measurements of channel widths and assessments of the ecological impact of hydrological changes.

The results confirm that satellite technologies are an effective tool for monitoring water bodies and analyzing flood phenomena. They not only allow for the identification of water bodies, but also, as previously mentioned, the Sentinel-1, Sentinel-2, and Landsat 8-9 satellite missions can be used to study the young river landscapes of the Prut and Cheremosh Rivers. The spatial resolution of these missions is 10 m for Sentinel-1 (radar images), 10–20 m for Sentinel-2 (optical images), and 30 m for Landsat 8-9 (optical images). The suitability of their use depends on the width of the young river landscape,

the specifics of the hydrological regime (channel discharge), and the characteristics of channel formation.

The Prut River channel in the studied section has a width of up to 60 m during the low-water period and up to 150 m during floods. In the mouth area, due to the confluence with the Cheremosh River, the channel width increases further. During floods, according to figures 2, 4, and 6, the channel width can reach up to 230 m. The young river landscape in this section has a width of 800–1500 m, allowing for the application of satellite imagery to analyze morphological changes, including shoreline dynamics and floodplain processes [monograph]. At the confluence of the Prut and Cheremosh Rivers, our field studies estimate the width of the young river landscape to be 1.0–2.6 km, which is sufficient for monitoring using Sentinel-1 and Sentinel-2.

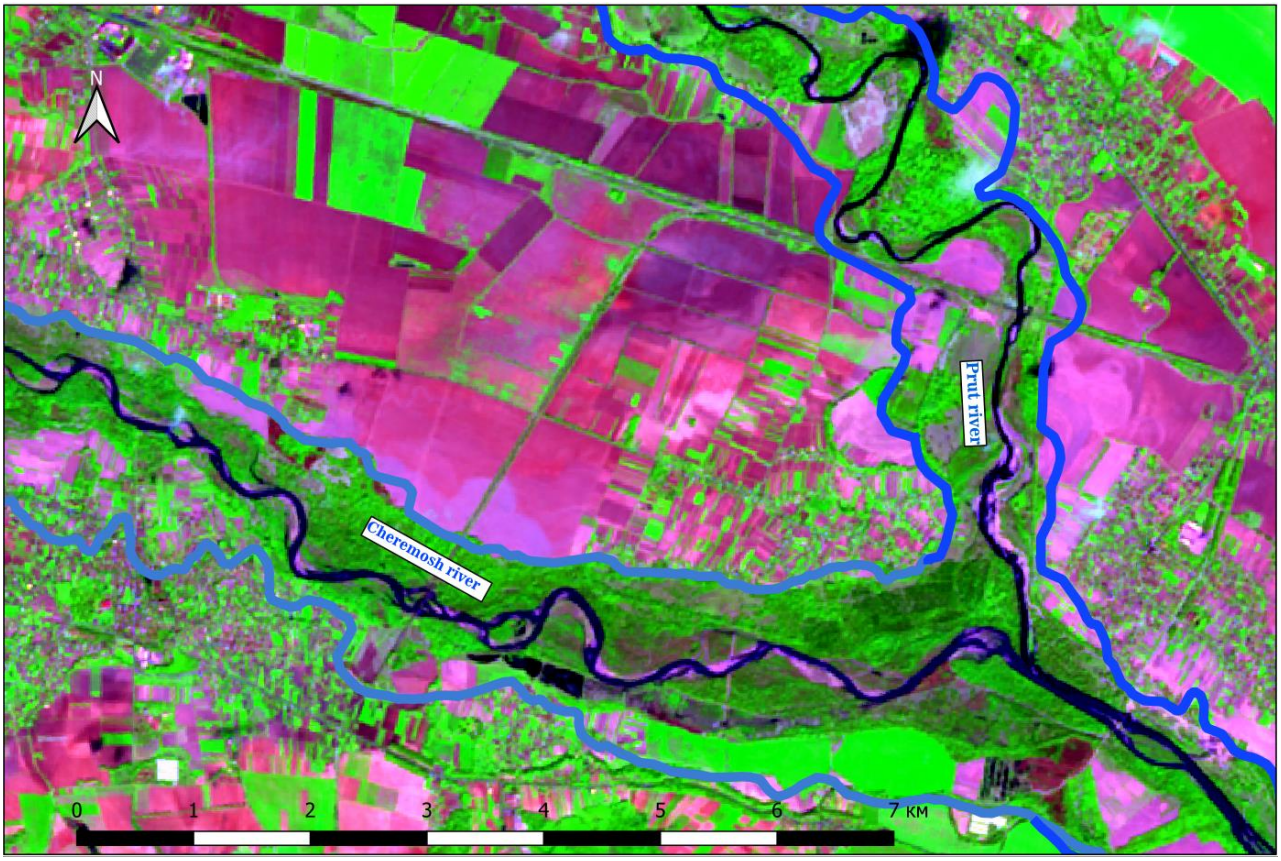

Figure 8: Sentinel-2 (SWIR) image of the junction of the Prut and Cheremosh Rivers during the low-water period (April 27, 2024), with overlaid boundaries based on the methodology for identifying young river landscapes

On the Cheremosh River, the channel width ranges from 20–40 m during the low-water period, increasing to 50–70 m during floods. The young river landscape in this section has a width of 1200–2000 m, making it feasible to use satellite images to analyze channel dynamics and riverine processes. Figures 1–8 clearly illustrate changes in channel position over four years, as well as abandoned river channels, drying branches, and a multi-channel system. Sentinel-1 is particularly useful for monitoring channel changes

caused by flood processes, as it operates independently of atmospheric conditions. Sentinel-2 also enables floodplain monitoring, though its effectiveness decreases under cloud cover. Landsat 8-9, due to its lower spatial resolution, is less suitable for studying narrow river sections. A spatial resolution of 10–30 meters does not allow for clear differentiation of shoreline changes in narrow sections, making it difficult to identify channel-forming processes and erosion changes.

Optical satellite missions such as Sentinel-2 and Landsat 8-9 are sensitive to cloud cover, which can significantly reduce image quality. This is particularly relevant for regions with high precipitation frequency, such as the Prut and Cheremosh river basins. During flood periods or seasonal transitions, there is a high probability of acquiring images unsuitable for analysis due to cloud interference. In contrast, Sentinel-1 radar imagery is less affected by atmospheric conditions, enabling continuous monitoring regardless of weather factors, making it more suitable for tracking channel processes in dynamic river systems.

In this study, the integration of satellite imagery (Sentinel-1, Sentinel-2, and Landsat 8–9) and GIS technologies provided a comprehensive view of how young river landscapes in the Prut and Cheremosh basins evolve under varying hydrological conditions. The findings highlight the individual contributions of each satellite mission to detecting channel shifts, floodplain inundation, and alluvial processes. Sentinel-1's synthetic aperture radar (SAR), especially in VH polarization mode with radiometric terrain correction, proved essential for mapping the rivers regardless of weather or daylight constraints. During flood events, such as in June 2020, the radar imagery revealed significantly widened channels and extensive floodplain inundation. In contrast, in low-flow conditions observed in April 2024, the channels appeared markedly narrower. By comparing multi-temporal data, researchers identified areas prone to rapid erosion along the outer banks of meander bends, as well as fresh sediment deposits that formed lighter patches in the imagery once floodwaters receded.

Sentinel-2's higher spectral resolution, particularly in the near-infrared (NIR) and shortwave infrared (SWIR) bands, allowed clear differentiation between flooded and dry surfaces, refining floodplain boundaries and enabling moisture-level analysis. Using false color composites, researchers detected dark patches showing water coverage in flood conditions and more vibrantly colored areas representing vegetation growth during low-water periods. This detailed view of seasonal floodplain dynamics is vital for understanding localized moisture gradients and the periodic exposure of nutrient-rich alluvial deposits, which in turn encourages rapid vegetation expansion. Meanwhile, Landsat 8–9, despite its coarser spatial resolution, provided an extended historical archive for analyzing long-term hydromorphological trends. By examining images spanning multiple years, researchers captured recurring patterns of flood events, sedimentation, and shifts in channel alignment. The thermal infrared data from Landsat also helped detect temperature differentials linked to shallow versus deeper water zones, revealing potential ecological stress points and habitat preferences.

Synthesizing the insights from multiple data sources within a GIS environment enabled precise mapping of water boundaries and quantification of channel width variations. In the Prut River alone, widths ranged from around 60 meters at low water to as much as

150–230 meters during floods. Areas susceptible to frequent inundation were delineated, revealing zones of notable wetland habitat value, albeit with heightened flood risk to nearby settlements. Erosion hazards were particularly evident where the channel banks had visibly shifted, signifying localized hotspots warranting closer observation and possible intervention. Combining satellite data with geoinformation techniques significantly enhanced the understanding of the complex processes that shape young river landscapes. Sentinel-1 excelled at capturing channel dynamics under all weather conditions, Sentinel-2 offered high-resolution spectral differentiation of water and vegetation, and Landsat 8–9 contributed a crucial long-term perspective for detecting inter-annual changes. Taken together, these findings not only elucidate flood extents, erosion patterns, and seasonal shifts in river morphology but also inform more robust flood risk assessments, habitat conservation efforts, and sustainable planning strategies. It is important to note that all satellite images used in our assessment effectively identify the zone of young river landscapes (Figure 8). The delineated young river landscape zones are characterized by high moisture levels and the presence of significant water reserves in biomass.

Some discrepancies in the blue-outlined young river landscape zones are due to differences in methodology. Researchers from Yuriy Fedkovych Chernivtsi National University (Pasichnyk, 2012; Yushchenko, 2019; Yushchenko, Honchar and Hryhoriichuk, 2017; Yushchenko *et al*., 2022) base their work on natural, pre-anthropogenic delineations of river landscapes, which result from detailed local terrain analysis.

Discussion

The application of remote sensing (RS) and Geographic Information Systems (GIS) methods, as described in this research, has demonstrated substantial potential in analyzing the dynamics of young river landscapes. However, there are inherent limitations and scalability considerations that must be addressed. Firstly, the accuracy of remote sensing-based assessments depends heavily on the resolution of satellite imagery. Although Sentinel-1, Sentinel-2, and Landsat 8-9 offer considerable spatial and spectral resolutions for monitoring young river landscapes, they still might not capture fine-scale processes, such as subtle morphological changes or micro-scale hydromorphological processes. Additionally, cloud cover and atmospheric disturbances significantly limit the temporal availability and quality of optical satellite data, leading to potential gaps in temporal analysis.

Another limitation is related to the calibration and validation of remote sensing data, which necessitates field surveys and ground truthing. This becomes particularly challenging when scaling up the method for larger river basins or in regions with limited accessibility. The harmonization of Sentinel-2 and Landsat data, such as in the NASA Harmonized Landsat and Sentinel-2 (HLS) project, addresses some of these challenges by providing frequent and high-resolution observations that improve land and water surface monitoring (NASA, 2023). Regarding scalability, the methodologies employed using platforms such as QGIS, ArcGIS, and EO Browser are highly scalable from local to regional studies. Nevertheless, computational resources and data storage requirements increase significantly when handling large-scale datasets. Future implementations must

therefore consider these constraints and adopt cloud computing solutions or other distributed data processing systems (USGS, 2021).

Moreover, the use of geospatial and machine learning algorithms for analysis can enhance the robustness of identifying and monitoring landscape changes. Recent applications of integrating remote sensing-derived indices with machine learning algorithms have demonstrated improved accuracy and efficiency. For example, studies comparing the performance of Sentinel-2 and Landsat data for surface water mapping highlight the advantages of multi-source data integration in water body delineation (Copernicus, 2022). Recent studies leveraging satellite observations further illustrate the versatility and effectiveness of remote sensing technologies in landscape and climatic research. Studies such as "Dual-satellite (Sentinel-2 and Landsat 8) remote sensing of supraglacial lakes in Greenland" (Andrew G. Williamson *et al*., 2018) and "Recent Applications of Landsat 8/OLI and Sentinel-2/MSI for Land Use and Land Cover Mapping: A Systematic Review" (Chaves, Picoli and Sanches, 2020) highlight the potential of satellite data in assessing landscape changes, particularly in hydrological and glaciological applications. Moreover, systematic reviews of remote sensing applications in land use change have underscored the effectiveness of combining Sentinel-2 and Landsat imagery in various environmental studies (Chaves, Picoli and Sanches, 2020).

Despite certain limitations, the methodological framework presented here provides a strong foundation for monitoring and analyzing dynamic river landscapes. Continued advancements in satellite technology, coupled with emerging machine learning techniques, promise substantial improvements in both the precision and scalability of landscape monitoring methods. Further research and methodological enhancements are recommended to improve applicability and accuracy at broader scales. The differences observed in our results compared to other studies stem from the specific focus on our research object and the practical application of methodologies developed by other researchers. While much of the existing research is dedicated to the development and optimization of remote sensing (RS) and geographic information systems (GIS) techniques, we concentrated on utilizing these advancements for an in-depth analysis of the young river landscapes of the Prut and Cheremosh rivers. This approach provided new practical insights into localized hydromorphological processes.

Several studies, such as those by Andrew G. Williamson et al. (2018) and Chaves, Picoli and Sanches (2020), offer detailed methodological frameworks for employing Sentinel-2 and Landsat data in mapping water bodies and analyzing landscape changes. Rather than creating new algorithms, we adopted and adapted these approaches to explore specific phenomena in the Carpathian river systems. This allowed us to validate the applicability of these methods under unique hydrological and morphological conditions. For instance, Sentinel-1 SAR data, known for its robustness in diverse weather conditions, was employed to monitor channel dynamics effectively, while Sentinel-2 optical data provided detailed spectral insights into water bodies. Landsat 8–9, though offering lower spatial resolution, proved valuable for identifying long-term trends due to its extensive historical archive. Unlike research that focuses on inter-comparisons of these platforms, our study used them collectively to identify active channel-forming zones during both flood and low-water periods.

Localized outcomes of our study, such as identifying shoreline changes, alluvial deposits, and channel expansion during floods, highlight processes that are often overlooked in broader regional analyses. By combining spectral indices and satellite imagery with visual and field observations, we successfully tailored existing methods to address specific challenges posed by the young river landscapes of the Carpathians. Tools like QGIS, ArcGIS, and EO Browser, widely regarded for their scalability, were instrumental in producing detailed digital maps that tracked hydromorphological changes with high accuracy. While platforms such as these are typically discussed in the context of larger-scale applications, we demonstrated their effectiveness in resolving local-level issues, such as monitoring shoreline dynamics and active channel processes. Findings of this study also extend beyond methodological advancements by providing actionable recommendations for flood risk management and sustainable resource planning. Through an analysis of channel dynamics, we identified areas prone to significant expansion and floodplain inundation, which are critical for risk assessments. Such insights align with the growing demand for integrating RS and GIS technologies into decision-making processes, ensuring their application contributes not only to scientific understanding but also to practical solutions for ecological preservation and socio-economic development.

Conclusions

As a consequence of this investigation, the established objectives were successfully attained, culminating in the following conclusions:

1. GIS technologies and remote sensing (RS) methods are effective tools for studying young river landscapes. A review of scientific publications demonstrated that satellite data significantly enhance mapping and monitoring capabilities for tracking river system changes.
2. Evaluation of Sentinel-1, Sentinel-2, and Landsat 8–9 satellite images revealed varying degrees of suitability for identifying river landscapes. Sentinel-1 (SAR) is the most effective for monitoring channel dynamics regardless of weather conditions. Sentinel-2 (optical data) enables detailed analysis of water bodies across different spectral ranges. Landsat 8–9 supports long-term monitoring of river ecosystem changes but has a lower spatial resolution compared to Sentinel missions.
3. Morphological analysis of the Prut and Cheremosh Rivers using satellite images across different hydrological phases (flood and low-water periods) allowed for the identification of active channel-forming zones. During the flood period, channel expansion and flooding of adjacent floodplains were observed, whereas the low-water period revealed channel narrowing, along with the visual identification of alluvial deposits and alluvial beaches.
4. The use of geoinformation technologies (QGIS, ArcGIS, and EO Browser) enabled the creation of digital maps of young river landscapes and the identification of shoreline changes and alluvial processes. The study confirmed that spectral indices are valuable for tracking the dynamics of channel processes within the young river landscapes of the Prut and Cheremosh Rivers.

The findings of this research offer a crucial knowledge base for policymakers to improve flood risk assessment and create sustainable resource management strategies. By leveraging RS data and GIS-based analysis of hydromorphological processes, decision-makers can: improve early warning systems and flood hazard mapping by monitoring real-time channel dynamics and floodplain changes; prioritize conservation efforts and land-use planning in rapidly transforming riverine areas; integrate science-based evidence into policy frameworks, ensuring that interventions in young river landscapes balance ecological preservation with socio-economic needs.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*	*Author 3*	*Author 4*	*Author 5*
Conceived and designed the research or analysis	Yes	No	No	Yes	No
Collected the data	Yes	Yes	No	No	Yes
Contributed to data analysis & interpretation	Yes	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	Yes	Yes	Yes	Yes	Yes
Editing of the article/paper	Yes	Yes	Yes	Yes	Yes
Supervision	No	Yes	No	Yes	Yes
Project Administration	Yes	No	No	No	No
Funding Acquisition	No	No	No	No	No
Overall Contribution Proportion (%)	20	20	20	20	20

Funding
No financial support was received for the research and writing of this article.

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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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